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Individualized body geometry correction factor (K_B) for use when predicting body composition from bioimpedance spectroscopy

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Conflict of interest

Author Ward consults to ImpediMed Ltd., manufacturer of impedance devices. ImpediMed Ltd. had no involvement in the concept, design or execution of these study nor in the preparation of the manuscript. All other authors have no relevant conflicts of interest to report.

ABSTRACT (250 words)

Objective: Prediction of body composition from bioimpedance spectroscopy (BIS) measurements using mixture theory-based biophysical modelling invokes a factor (K_B) to account for differing body geometry (or proportions) between individuals. To date, a single constant value is commonly used. The aim of this study was to investigate variation in K_B across individuals and to develop a procedure for estimating an individualized K_B value.

Approach: Publicly available body dimension data, primarily from the garment industry, were used to calculate K_B values for individuals of varying body sizes across the life-span. The 3-D surface relationship between weight, height and K_B, was determined and used to create look-up tables to enable estimation of K_B in individuals based on height and weight. The utility of the proposed method was assessed by comparing fat-free mass predictions from BIS using either a constant K_B value or the individualized value.

Results: Computed K_B values were well fitted to height and weight by a 3-D surface ($R^2 = 0.988$). Body composition was predicted more accurately compared to reference methods when using individualized K_B than a constant value in infants and children but improvement in prediction was less in adults particularly those with high body mass index.

Significance: Prediction of body composition from BIS and mixture theory is improved by using an individualized body proportion factor in those of small body habitus, e.g. children. Improvement is small in adults or non-existent in those of large body size. Further improvements may be possible by incorporating a factor to account for trunk size, i.e., waist circumference.

1. Introduction

Bioelectrical impedance technologies have become increasingly popular for the assessment of human body composition in vivo (Ward 2021). Bioelectrical impedance analysis (BIA) methods fall into two categories: estimation of body composition based on empirically-derived prediction equations for total body water (TBW) (Kyle *et al* 2004b, 2004a) or fat-free mass (FFM), or estimations based on a biophysical model derived from mixture theory. originally developed by Hanai to describe the electrical properties of emulsions ((Hanai 1968) Mixture theory subsequently formed the basis of a biophysical model to describe the relationship between the body's electrical impedance (or resistance) and body water volumes, TBW and its sub-compartments intra- and extracellular water (ICW and ECW respectively) (De Lorenzo *et al* 1997) and comprehensively reviewed by Matthie (Matthie 2008). The first approach typically uses electrical resistance measured at a single or few frequencies (single- or multi-frequency bioelectrical impedance analysis; SFBIA, MFBIA respectively) while the second adopts a spectroscopic approach (bioelectrical impedance spectroscopy, BIS) measuring resistance over a range of frequencies and using Cole modelling to estimate resistance at zero and infinite frequencies representative of ECW and TBW respectively (Ward *et al* 2015a, Stahn *et al* 2012, Cornish *et al* 1993) and then applying these measured resistances in the mixture theory-based biophysical model. The algorithms underpinning this biophysical model are complex and have been described in detail elsewhere (Ward *et al* 2015a, Stahn *et al* 2012). Irrespective of which approach is adopted, BIA is based on the relationships that, for a homogeneous uniform cylindrical conductor, resistance is proportional to conductor length and inversely proportional to cross-sectional area. From these relationships and simple geometry of a cylinder yields

$$Volume = \rho \frac{L^2}{R} \quad \text{.....[1]}$$

where L = conductor length (cm); R = resistance (ohm) and ρ is the specific resistivity of the conductive volume (ohm.cm). Clearly, application of this model to the human body is problematic since the body is neither homogeneous nor a simple cylinder. The biophysical model attempts to account for this by

assuming homogeneity of the body water compartments and that body consists of five inter-connected cylinders representing the trunk and the four limbs.

De Lorenzo et al. attempted to account for the complex cylindrical geometry (interconnected segments of the leg, trunk and arm in wrist-ankle impedance measurements) of the human body by modifying Equation 1 to include a body proportion factor, K_B, that relates to the relative proportions of the leg, arm and torso (Equation 2) (De Lorenzo *et al* 1997)

$$Volume = K_B \, \rho \, \frac{L^2}{R} \quad \text{.....[2]}$$

K_B can be calculated from anthropometric measurements (segment lengths and girths) and a value of 4.3, originally determined by de Lorenzo et al. (De Lorenzo *et al* 1997), is commonly used. This value was determined from anthropometric measurements obtained from United States army personnel (De Lorenzo *et al* 1997, Gordon *et al* 1989). The assumption of applicability of this value to all populations irrespective of individual body habitus has, however, been criticized as incorrect and contributing to inaccuracy in estimations of body composition when using mixture theory (Kagawa *et al* 2014, Cox-Reijven and Soeters 2000, Cox-Reijven *et al* 2002, Ward *et al* 2015a, Moissl *et al* 2006, Jødal 2010, Ward *et al* 1998). This is highlighted when the biophysical approach is used to estimate body composition in babies where a K_B value of 3.8 was found to be more appropriate (Collins *et al* 2013), while values of up to 6.5 have been observed in the obese (Cox-Reijven and Soeters 2000). This has led to a call for personalization of K_B parameters used in BIS and mixture theory prediction of body composition (Seoane *et al* 2015). The aims of the present study were to assess the range of K_B observed in the general population across a range of body habitus from birth to adulthood and to develop a procedure for estimating an individualized K_B value based upon simple anthropometric measurements of height and weight.

2. Methods

2.1. Source data

Anthropometric data were primarily extracted from standard tables of body measurements provided by American Society for Testing and Materials (ASTM) International primarily for use in the apparel industry (Godil and Ressler 2008). Data are available in a number of separate ASTM standards for both sexes across the lifespan (Supplemental Table 1). The tables of data are constructed from various data sources including U.S. Department of Commerce through (ASTM International 1971) and subsequent reports, the Caesar Study (Robinette *et al* 2003), the SizeUSA study (TC2 2006), various CDC Anthropometric Reference Data reports, e.g. (McDowell *et al* 2009) according to internationally recognized principles on standardization and defined in ASTM-defined standard D5219 (ASTM International 2015a). The data provided vary slightly for different population groups but included all body dimensions to calculate K_B, i.e. arm length and circumference, leg length and circumference, and trunk length and circumference in addition to height or crown-heel length for babies. Standards are generally presented in both SI (metric) and inch-pound units; where only inch-pound units were available, data were converted to metric equivalents. Data are provided as population mean values stratified by garment size (US) within each body size category used within the garment industry, e.g., “Misses Petite”, “Misses tall”, “Boys” etc.

ASTM standards data for babies and infants are sparse. Additional data were sourced primarily from the studies of Merlob and colleagues (Merlob *et al* 1983, 1986, Sivan *et al* 1984, Merlob *et al* 1984) and Kwok et al. (Kwok *et al* 2007). Additional data was obtained from a sub-study of the Growing Up in Singapore Towards healthy Outcomes (GUSTO) study (Tint *et al* 2016). A total of 344 individual data sets were available for analysis.

2.2 Calculation of K_B

The body proportion coefficient, K_B, was calculated using the formula described by de Lorenzo et al (De Lorenzo *et al* 1997):

$$K_B = \frac{1}{L^2}\left[\left(\frac{L_l}{C_l^2} + \frac{L_t}{C_t^2} + \frac{L_a}{C_a^2}\right)\left(2L_aC_a^2 + 2L_lC_l^2 + L_tC_t^2\right)\right] \quad \text{.....[3]}$$

where L = length (cm); C = circumference (cm) and subscripts indicate body region: t = trunk, l = leg and a = arm. Leg length was assumed equivalent to ASTM-designated "crotch height"; trunk length equivalent to ASTM-designated "cervicale to crotch height" and arm length equivalent to ASTM-designated "underarm length" (ASTM International 2015a). Circumference values were calculated as the mean of ASTM-designated chest and waist girths for the trunk, mid-thigh and ankle girths for the leg and mean of upper arm and wrist girths for the arm. Detailed description of terminology and diagrams showing anatomical sites of measurement for these data are provided in (ASTM International 2015a). Body volume (excluding hands, feet and head) was also calculated from these dimensions assuming cylindrical geometry for body segments as for the calculation of K_B. Height and weight were also extracted from the available data. Weight was not provided for four data sets and hence was imputed using a regression equation for calculated body volume against weight for data sets where weight was available.

2.3. Relationship of K_B with height and weight

The relationship between height, weight and K_B was explored based on treating the data as a set of three-dimensional points. Height and weight represented a two-dimensional X-Z grid with K_B plotted as the Y values in the vertical dimension. Three-D surface mesh plots for the irregularly spaced data were produced using NCSS version 10.0.10 (NCSS Statistical Software. NCSS, LLC. Kaysville, Utah, USA, ncss.com/software/ncss). Separate plots were prepared for males and female infants. Surface fitting of the data was accomplished using the automated fitting routines of Table Curve 3D and the Watson

interpolation algorithm to a uniform grid (Table Curve 3D version 4 Systat software, San Jose, California). Separate plots were prepared for males and female infants. Surface fitting of the data was accomplished using the automated fitting routines of Table Curve 3D and the Watson interpolation algorithm to a uniform grid.

2.4. Prediction of K_B from height and weight

TableCurve3D version 4.0.05 (Systat Software Inc., San Jose) was used to create interpolated values from the modelled surface at 5 kg (from 5 to 200 kg) and 5 cm (from 5 to 200 cm) intervals for each sex separately. The resulting height, weight, K_B data matrices was exported to Excel to provide 2-dimensional look-up data tables. The predicted K_B value for a given height and weight data pair can be calculated from these data tables using the Excel bilinear interpolation function, InterpolateXY (Stelling Consulting, Alphen aan den Rijn, The Netherlands).

2.5. Performance assessment of individualized K_B values in prediction of body composition

Body composition was predicted from BIS data for existing data sets for 4.5-month-old infants (Lingwood *et al* 2012); children aged 6.5 to 9.5 years (Al-Ati *et al* 2015, Ward *et al* 2015b); overweight and obese adolescents aged 10 to 18 years (Wan *et al* 2014) and healthy adults aged 18 to 49 years from the 1999-2000 NHANES survey (National Center for Health Statistics 2012). Although different impedance devices were used in each of these studies [ImpediMed SFB7 (Lingwood *et al* 2012, Al-Ati *et al* 2015, Ward *et al* 2015b); Tanita MC-180MA, (Wan *et al* 2014); Xitron Hydra 4200 (National Center for Health Statistics 2012)] each provided the requisite impedance data for use in the biophysical body composition model – resistance at zero frequency (R0) and resistance at infinite frequency (Rinf). The reader is referred to the primary source citation for full methodological information. In order to facilitate comparison, these raw

resistance data were analysed with the same biophysical model software (Bioimp BatchBCA version 1.4.0.0, ImpediMed Ltd., Brisbane, Australia) as described previously ((Ward *et al* 2015a) using the same parameters (ρ_i = 1018 and 1023.5 ohm.cm and ρ_e = 309.9 and 316.1 ohm.cm for males and females respectively, body density (Db) = 1.05 g/mL and hydration fraction of 0.732) as described previously (Ward *et al* 2015a) except for K_B which was either set as a fixed value (group F) of 4.3 (De Lorenzo *et al* 1997) or the individualized values (group I) derived as described above (section 2.4). For infants (data of Lingwood *et al* 2012), hydration fraction was individualized according to Fomon et al. (Fomon *et al* 1982) and these data were additionally analysed using BIS parameters determined for neonates (group F2) by Collins et al. (Collins *et al* 2013). Data comparison was based upon predicted fat-free mass (FFM) and was compared to reference FFM from the original source data.

2.6 Statistical analysis

Normality of data was assessed using Kolmogorov-Smirnov test. Since K_B was not normally distributed, comparison of calculated and imputed K_B values was performed using Passing and Bablok regression that makes no assumptions about the underlying data distributions. Agreement between FFM predicted by BIS using either fixed K_B or individualized K_B values was assessed by concordance correlation, limits of agreement (LOA) analysis and determination of median absolute percentage error (MAPE). All statistical analyses were performed with either MedCalc® Statistical Software version 20.013 (MedCalc Software Ltd, Ostend, Belgium; https://www.medcalc.org; 2021) or JASP version 0.15 (University of Amsterdam, https://jasp-stats.org). Surface fitting was accomplished using Table Curve 3D version 4.0.05 (Systat Software Inc., Richmond, USA, https://systat.com) and plotted using either Slidewrite v7.01 (Advanced Graphics Software, Rancho Santa Fe, USA) or NCSS v10.0.10 (NCSS LLC. Kaysville, USA https://ncss.com/software/ncss).

3. RESULTS

3.1 Anthropometric characteristics of K_B-data sources

The distributions of height and weight for participants within each data set are presented in Figure 1.

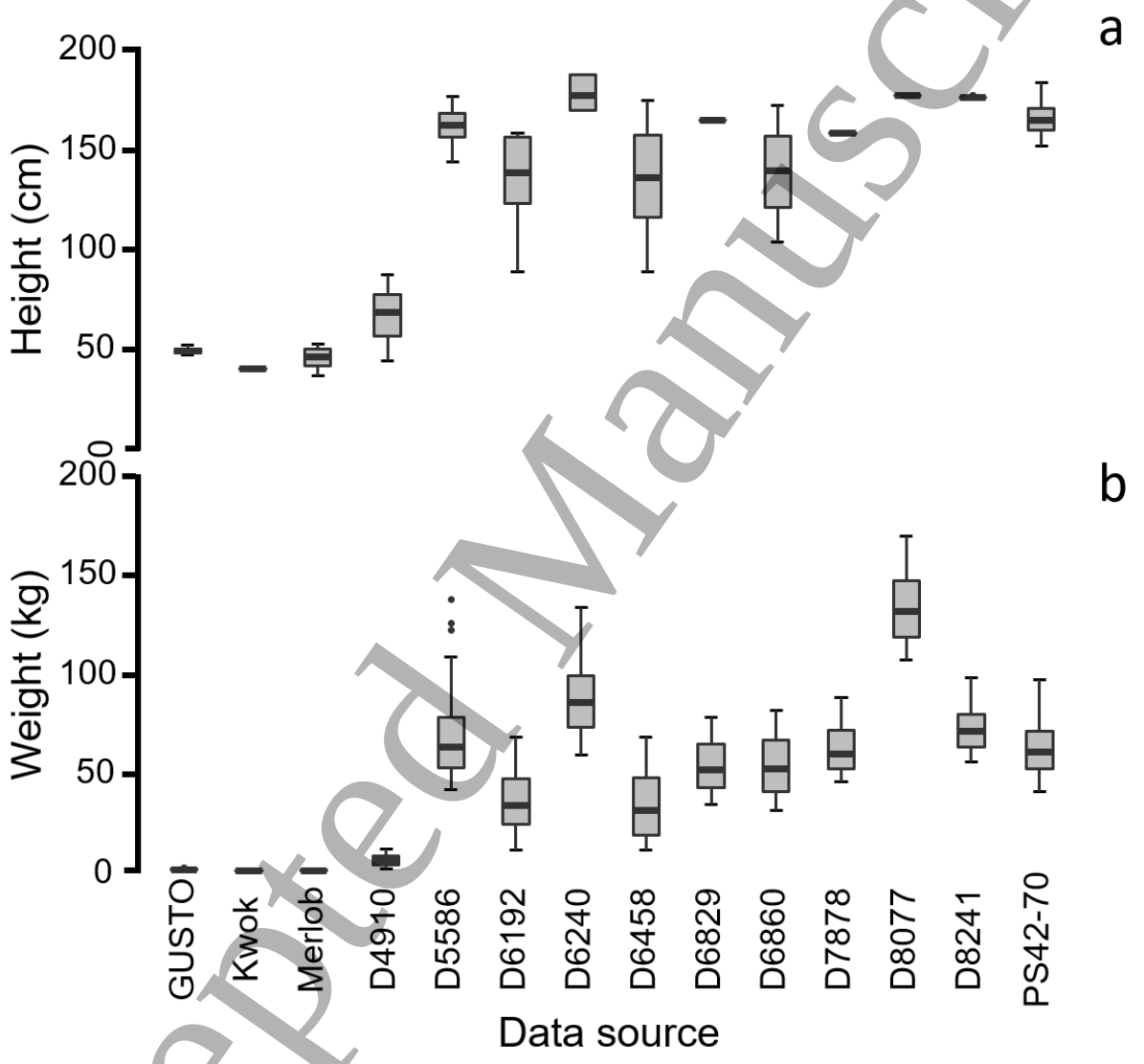

Figure 1. Distributions of height (Panel a) and weight (Panel b) for each data source. Box plots represent the median as the central line, the first and third quartiles as the edges of the box, 1.5 x the inter-quartile range above and below the box as lines and outliers beyond these bounds as symbols (•).

Height (crown-heel supine length for babies) ranged from 35.8 to 188 cm with weight ranging from 1.6 to 170.1 kg (Table 1).

TABLE 1 HERE

Both height and weight were bi-modally distributed with, notably relative fewer data in the 60 to 130 cm height and 15 to 40 kg weight ranges reflecting few school-aged children in the data sets (Supplemental Data Figure 1).

Table 1. General characteristics of source data for generation of K_B values[2]

Data source[1]	Group	Sex	Age (y)	N[3]	Height (cm)	Weight (kg)	BMI (kg/m^2)	K_B
ASTM D5586 (ASTM International 2002)	"Junior", "Junior petite", "Petite", "Misses" & "Misses tall"	Female	>55	47	161.9 ± 8.3 (144.1 – 177.3)	70.0 ± 22.6 (43.0 – 138.2)	26.4 ± 7.1 (17.9 – 51.7)	4.0 ± 0.4 (3.6 – 5.4)
ASTM D6829 (ASTM International 2015b)	"Juniors"	Female	na[4]	11	165.1	54.9 ± 14.6 (35.3 – 79.2	20.2 ± 5.3 (13.7 – 29.1)	3.7 ± 0.4 (3.2 – 4.3)
ASTM D7878 (ASTM International 2013)	"Misses petite"	Female	na	24	158.7	63.7 ± 13.1 (46.8 – 89.0)	25.3 ± 5.2 (18.6 – 35.3)	4.0 ± 0.1 (3.8 – 4.2)
ASTM D6192 (ASTM International 2019b)	"Regular", "slim" & "Plus"	Female	<12.5	34	136.2 ± 20.6 (88.9 – 158.7)	37.4 (12.1 – 69,1)	19.1 ± 3.6 (14.0 – 27.8)	4.0 ± 0.1 (3.8 – 4.3)
ASTM D6240 (ASTM International 2021)	"Mature"	Male	>35	48	178.6 ± 7.4 (170.2 – 188.0)	88.6 ± 18.8 (60.3 – 134.1)	27.8 ± 5.9 (18.7 – 41.9)	4.0 ± 0.3 (3.3 – 4.6)
ASTM D6458 (ASTM International 2019c)	"Boys Slim" & "Regular"	Male	< 15	24	136.5 ± 26.2 (88.9 – 175.3)	35.5 ± 17.7 (12.1 – 69.1)	16.5 ± 2.5 (12.5 – 20.7)	4.0 ± 0.1 (3.8 – 4.1)
ASTM D8077 (ASTM International 2016)	"Mature large"	Male	na	7	177.8	135.0 ± 22.0 (107.8 – 170.1)	42.7 ± 6.9 (34.1 – 53.8)	4.7 ± 0.1 (4.6 – 4.8)

Table 1 continued. General characteristics of source data for generation of K_B values[2]

Data source[1]	Group	Sex	Age (y)	N[3]	Height (cm)	Weight (kg)	BMI (kg/m^2)	K_B
ASTM D8241 (ASTM International 2019d)	"Young men"	Male	na	14	176. ± 8.5 (176.5 – 177.8)	73.7 ± 12.9 (56.5 – 99.0)	23.6 ± 4.0 (18.1 – 31.3)	3.9 ± 0.3 (3.5 – 4.6)
ASTM D4910 (ASTM International 2019a)	Neonate & Infants	Combined	Birth to 2	8	66.9 ± 15.2 (44.4 – 87.6)	7.5 ± 1.2 (2.8 – 12.7)	16.5 ± 2.1 (12.6 – 18.6)	3.2 ± 2.8 (2.8 3.4)
PS42-70 (ASTM International 1971)	"Junior", "Junior petite", "Petite", "Misses" & "Misses tall"	Female	na	37	161.3 ± 8.7 (147.3 – 179.1)	57.7 ± 14.2 (35.5 – 129.3)	22.0 ± 3.7 (15.7 – 30.0)	4.40 ± 0.2 (3.6 – 4.4)
GUSTO (Tint *et al* 2016)	Neonate	Male	Birth	23	48.0 ± 1.4 (46.0 – 51.0)	2.8 ± 0.3 (2.3 – 3.8)	12.1 ± 1.3 (10.2 – 14.7)	2.1 ± 0.3 (1.7 _ 2.8)
		Female		7	48.3 ± 1.8 (46.0 – 50.5)	2.9 ± 0.2 (2.6 – 3.1	12.3 ± 0.6 (11.3 – 13.2)	2.3 ± 0.4 (1.7 – 2.8)
Kwok (Kwok *et al* 2007)	Neonate	Female	Birth	1	39.4	2.0	8.8	2.9
Merlob (Merlob *et al* 1984, Sivan *et al* 1984, Merlob *et al* 1983)	Neonate	Male	Birth	15	45.3 ± 4.8 (37.3 – 51.4)	2.1 ± 0.4 (1.6 – 2.1)	10.7 ± 2.0 (8.0 – 13.3)	1.9 ± 0.1 (1.7 _ 2.1)
		Female		15	44.5 ± 5.0 (35.8 – 50.4)	2.1 ± 0.4 (1.6 – 2.7)	10.6 ± 2.0 (7.3 – 13.2)	1.9 ± 0.2 (1.4 – 2.2)

[1]See Supplemental Data Table 1 for details of source data. [2]See Supplemental Table 2 for detailed anthropometric data used to generate K_B. [3]N=number of data points used, actual contributing participant numbers are larger (see Supplemental Data Table 1). [4]Not available. Data are presented as mean ± SD (range).

3.2 Computation of K_B

A bimodal distribution was also observed for K_B reflecting the similar distribution for height and weight (Supplemental Figure 2). K_B values ranged from 1.26 to 5.43. The 3-D surface distributions of K_B with height and weight are presented in Figure 2. Optimal surface fitting (maximum likelihood estimation) was achieved with Chebyshev cosine series bivariate 10^{th} order polynomial (coefficient of determination R^2 = 0.988). Similar surfaces were found for both males and females with generally larger K_B values associated with larger height-weight combinations. Neither surface was a smooth flat plane with a small but apparent peak at low weight-high length combinations. Surfaces were well fitted (coefficient of determination R^2= 0.988) and there was a strong correlation (r^2 = 0.930, SEE = 0.207, $P < 0.0001$) between K_B calculated according to Equation 3 and values imputed from the 3-D surfaces (Figure 3).

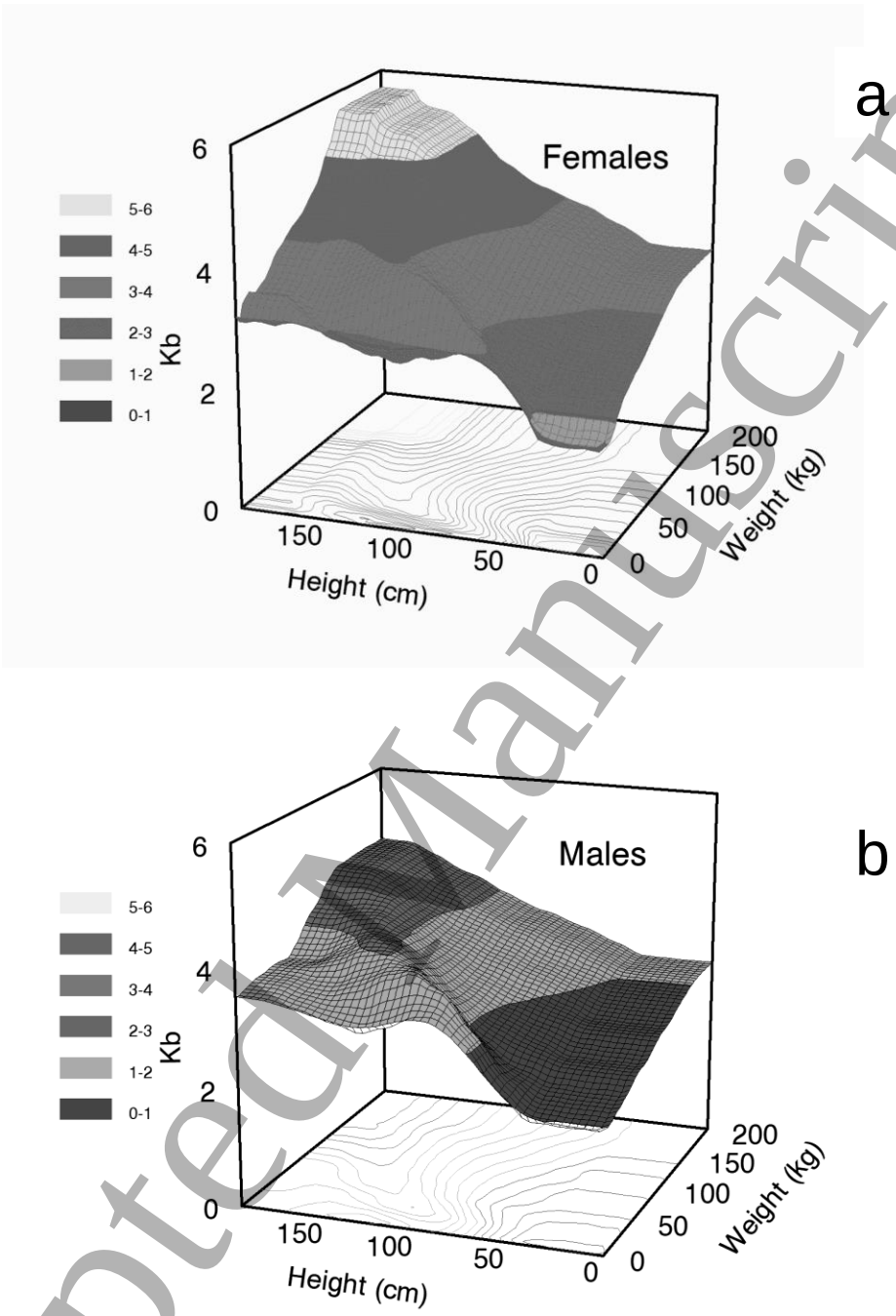

Figure 2. Three-dimensional surface plots of the relationship between height and weight and K_B

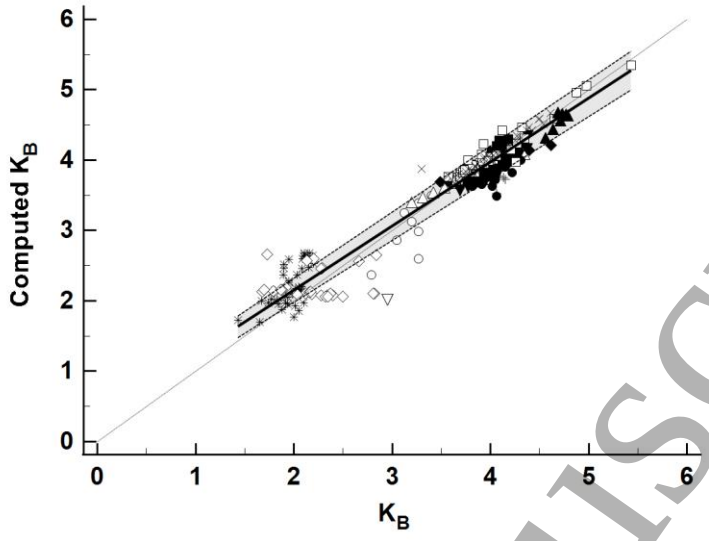

Figure 3. Relationship between calculated K_B from anthropometric parameters and the computed K_B from the 3-D surfaces. Data are presented as a Passing-Bablok regression with the line of best fit shown (—) overlaid on the line of identity (—). The shaded region represents the 95% confidence interval range. Individual data sources are represented by different symbols: ✕ D6240, ✚ D6458, ■ D7878, □ D5586, ◆ D8241, ● D6192, ◇ Gusto, △ D6829, ▽ Kwok, ▲ D8077, ▼ PS42-70, ✳ Merlob, ○ D4910 (see Supplemental Data Table 1 for details).

3.3 Comparison of individual and fixed K_B values for predicting body composition.

K_B values calculated from heights and weights for the comparison studies are presented in Table 2.

TABLE 2 HERE

There were approximately equal numbers of males and females in each cohort with cohort sizes ranging from 22 to 758 participants. Heights ranged from 61 (4.5 m infants) to 199.4 cm (adults) and weights from 5.4 to 144.5 kg with BMI values ranging from 12.3 to a maximum of 57.5 kg/m^2. Computed K_B values ranged from 2.5 to 5.5, generally increasing from neonates to high BMI adults (Table 2). Fat-free masses were smallest, not unexpectedly, for neonates with a minimum of 4.2 kg and the largest, 94.4 kg, for adults. Generally, FFM was overestimated by BIS compared to measured values. Overestimation was largest when a fixed K_B value was used and decreased by between 1.6 kg in neonates and 4.3 kg adult males (BMI 20-25 kg/m^2) when individualized K_B values were used. Improvement in prediction with the

use of individualized K_B was, however, limited to those participants with BMI values below 30 (WHO classification of overweight or below). Indeed in those participants with BMI values >30, i.e. WHO classification as obese, use of individual K_B values worsened prediction (Table 2). This was confirmed by lower MAPE values for the BMI <30 cohorts for individualized K_B calculations but higher MAPE values in the BMI >30 groups. Despite the improvement in population, mean prediction (smaller bias compared to measured FFM) by the use of individual K_B in the lower BMI groups there was no difference in the LOA. For neonates, the use of resistivity coefficients specific for neonates (Collins *et al* 2013) improved prediction compared to conventional fixed K_B BIS but this improvement was still less than that observed when individualized K_B values were used.

Table 2. Comparison of prediction of body composition using either a fixed value for K_B (F and F2) or individualised values (I).

Source Reference	Group	Sex Number	Height (cm)	Weight (kg)	BMI[1] (kg/m^2)	K_B	FFM[2] (kg)	K_B type	Predicted FFM (kg)	1.96 SD Limits of Agreement	MAPE[3] (%)
(Lingwood *et al* 2012)	Infants (4.5 months)	Female N = 25	66.2 ± 2.3 (62.2 – 69.6)	7.2 ± 0.9 (5.4 – 8.9)	16.5 ± 1.8 (13.8 – 20.5)	3.0 ± 0.06 (2.9 – 3.1)	5.4 ± 0.5 (4.3 – 6.3)	F	6.8 ± 1.1	-2.7 – 0.0	26.4
								F2	6.0 ± 0.9	-1.7 – 0.6	11.7
								I	5.2 ± 0.9	-0.8 – 1.3	5.4
		Male N = 25	64.5 ± 1.1 (61.0 – 67.7)	7.0 ± 0.6 (5.9 – 8.0)	16.7 ± 1.3 (13.9 – 19.4)	2.7 ± 0.07 (2.5 – 2.8)	4.9 ± 0.3 (4.2 – 5.6)	F	6.2 ± 0.9	-2.9 – 0.2	24.0
								F2	5.8 ± 0.9	-2.5 – 0.5	16.4
								I	4.6 ± 0.7	-1.0 – 1.5	10.0
(Ward *et al* 2015b)	6.5 – 9.5 years	Female N = 75	129.8 ± 6.4 (113.9 – 148.8)	33.9 ± 10.8 (19.1 – 65.5)	19.8 ± 5.1 (13.6 – 35.2)	3.9 ± 0.1 (3.7 – 4.1)	21.1 ± 3.9 (14.5 – 36.5)	F	23.6± 5.1	-5.7 – 0.8	11.2
								I	21.0 ± 4.8	-2.8 – 3.2	4.5
		Male N = 83	129.0 ± 7.4 (112.2 – 149.5)	33.6 ± 11.1 (18.2 – 76.5)	19.8 ± 4.7 (13.5 – 35.7)	3.9 ± 0.1 (3.6 – 4.2)	19.9 ± 4.4 (13.0 – 36.8)	F	22.5 ± 5.6	-6.0 – 0.8	12.5
								I	20.2 ± 5.4	-3.4 – 2.8	5.2
Wan (Wan *et al* 2014)	10 – 17 years	Female N = 29	159.6 ± 8.9 (144.0 – 178.0)	83.9 ± 19.7 (49.9 – 129.9)	32.5 ± 6.60 (22.8 – 47.7)	4.3 ± 0.3 (3.9 – 95.2)	43.0 ± 8.1 (31.1 – 63.8)	F	49.9 ± 9.5	-12.0 – 1.8	15.5
								I	50.1 ± 12.0	-16.1 – 1.9	16.8
		Male N = 29	165.3 ± 11.9 (139.0 – 186.0)	95.1 ± 21.0 (56.7 – 128.6)	34.6 ± 5.6 (21.9 – 48.6)	4.2 ± 0.2 (3.9 – 4.6)	52.8 ± 13.5 (27.0 – 80.0)	F	59.6 ± 14.4	-13.2 – -0.4	12.9
								I	59.4 ± 15.7	-14.7 – 1.4	13.2

[1]BMI= body mass index. [2]FFM = fat-free mass. [3]MAPE = median absolute percentage error. F = fixed K_B value = 4.3; F2 = fixed K_B value = 3.8. I = individualized K_B value.

Table 2 continued. Comparison of prediction of body composition using either a fixed value for K_B (F and F2) or individualised values (I).

Source Reference	Group	Sex Number	Height (cm)	Weight (kg)	BMI[1] (kg/m^2)	K_B	FFM[2] (kg)	K_B type	Predicted FFM (kg)	1.96 SD Limits of Agreement	MAPE[3] (%)
NHANES (National Center for Health Statistics 2012)	BMI <19.9	Female N = 74	161.0 ± 6.7 (145.6 – 174.5)	42.9 ± 11.6 (19.1 – 71.1)	18.5 ± 1.2 (14.8 -20.0)	4.2 ± 0.3 (3.7 – 4.7)	35.1 ± 4.0 (26.5 – 46.2)	F	37.3 ± 4.3	-6.0 – 1.6	7.3
								I	36.5 ± 4.3	-6.8 – 4.0	5.5
		Male N = 513	154.6 ± 17.1 (115.8 – 192.5)	48.1 ± 5.0 (39.3 – 59.8)	17.6 ± 1.6 (12.3 – 20.0)	3.7 ± 0.07 (3.6 – 3.9	34.7 ± 10.6 (14.3 – 59.3	F	37.6 ± 11.0	-7.0 – 1.2	8.9
								I	34.2 ± 9.9	-3.8 – 4.7	3.9
	BMI 20-24.9	Female N = 311	162.6 ± 6.9 (143.3 – 180.4)	60.3 ± 6.4 (42.8 -80.2)	22.7 ± 1.4 (20.0 – 24.9)	3.9 ± 0.06 (3.8 – 4.2	40.0 ± 4.5 (26.6 – 54.0)	F	43.7 ± 5.1	-8.6 – 1.1	9.5
								I	41.0 ± 5.0	-5.8 – 3.7	4.4
		Male N = 758	168.4 ± 12.5 (126.7 – 199.4)	64.0 ± 10.3 (34.0 – 88.7)	22.4 ± 1.4 (20.0 – 24.9)	3.8 ± 0.08 (3.6 – 4.0	50.1 ± 10.1 (19.8 – 74.9)	F	54.3 ± 10.6	-9.9 – 1.4	9.1
								I	50.2 ± 9.6	-6.0 – 5.7	4.1
	BMI 25-29.9	Female N = 250	161.7 ± 6.6 (1543.3 -179.4)	71.5 ± 7.2 (55.2 – 91.9)	27.3 ± 1.5 (25.0 – 29.9)	4.0 ± 0.06 (4.0 – 4.3	43.4 ± 4.8 (31.0 – 57.5)	F	48.2 ± 5.7	-9.9 – 0.5	10.9
								I	46.3 ± 5.7	-8.1 – 2.3	6.7
		Male N = 519	171.9 ± 9.7 (132.0 – 197.5)	80.9 ± 10.1 (45.3 – 108.4)	27.3 ± 1.4 (25.0 – 29.9)	4.0 ± 0.08 (3.9 – 4.3	58.6 ± 4.8 (25.6 -81.3)	F	64.3 ± 10.1	-12.6 – 1.3	9.8
								I	61.5 ± 10.0	-9.8 – 4.0	5.2
	BMI 30-39.9	Female N= 257	160.6 ± 7.1 (133.0 – 178.4)	88.1 ± 11.6 (65.5 – 125.5)	34.1 ± 2.8 (30.0 – 39.9)	4.3 ± 0.02 (4.1 – 5.2)	49.2 ± 6.3 (34.9 – 67.1)	F	55.3 ± 7.2	-13.1 – 0.9	12.5
								I	55.4 ± 8.3	-14.1 – 1.7	12.4
		Male N = 290	174.2 ± 8.8 (143.5 – 196.0)	101.7 ± 13.4 (62.0 – 134.4)	33.4 ± 2.5 (30.0 – 39.9)	4.3 ± 0.2 (4.1 – 4.7)	68.3 ± 10.0 (37.1 – 94.4)	F	75.3 ± 11.4	-15.9 – 1.9	9.7
								I	75.4 ± 12.7	-17.3 – 3.1	9.7
	BMI >40	Female N = 56	161.2 ± 6.3 (145.3 – 172.8)	114.7 ± 11.7 (89.8 – 144.5)	44.1 ± 3.4 (40.0 – 57.5)	4.8 ± 0.2 (4.4 – 5.5)	58.9 ± 6.2 (46.8 – 72.1)	F	68.1 ± 7.9	-18.8 – 0.5	14.7
								I	73.5 ± 10.4	-26.8 – -2.4	23.5
		Male N = 22	170.8 ± 5.1 (162.8 – 178.6)	124.8 ± 7.1 (111.3 – 138.1)	42.8 ± 2.1 (40 – 48.2)	4.5 ± 0.08 (4.4 – 4.6)	75.1 ± 6.3 (62.3 – 88.4)	F	82.8 8.8	-18.8 – 3.3	9.4
								I	85.7 9.6	-22.5 – 1.3	12.8

[1]BMI= body mass index. [2]FFM = fat-free mass. [3]MAPE = median absolute percentage error. F = fixed K_B value = 4.3; F2 = fixed K_B value = 3.8. I = individualized K_B value.

4. DISCUSSION

The present study has demonstrated that the use of a body proportion factor (K_B) personalized to the individual improves prediction of body composition from BIS data. This improvement was only seen in those individuals with BMI <30 kg/m^2. Conventional whole body, wrist to ankle, impedance measurements assumes that the body conforms to a simple single cylindrical geometry, which is clearly not the case. The body proportion factor attempts to account for the relative differences between the body segments (leg, trunk and arm) in shape and size. A value of K_B = 4.3 is commonly used irrespective of body habitus. Although it has been recognized previously that this value will not adequately represent relative body proportions in all individuals (Cox-Reijven *et al* 2002) and that K_B varies markedly between individuals even in a relatively homogeneous group of adults (Ward *et al* 2015a), little attempt has been made to correct for potential error introduced by use of an inaccurate K_B. Two approaches have been attempted. Firstly, Moissl (Moissl *et al* 2006) introduced a modification to BIS and mixture theory, termed BCS, body composition spectroscopy, that corrected the mixture theory equations according to the subjects BMI. While this approach has merit, its effectiveness is questionable in some populations (Ellegård *et al* 2009). The second approach has been to measure the impedance of each of the body segments separately and to calculate whole body composition from the segmental data (Ward 2012). The wide-spread adoption of this method has, however, been driven primarily by the development of the stand-on impedance analyser rather than to mitigate body shape errors in whole-body measurements. Notably, most of these devices are not BIS devices but single or multi-frequency devices that predict body composition from empirically-derived population-specific algorithms not mixture theory (Ward 2012).

It is feasible to personalize K_B for each individual by obtaining the required anthropometric measurements and using Equation 3. In practice this is unlikely to be adopted due to the logistics and time involved in obtaining the requisite anthropometric measurements. Furthermore, anthropometric measurements are susceptible to considerable measurement error and specially trained anthropometrists are required (Perini *et al* 2005). An

alternative is to approximate K_B for an individual based on more readily obtainable measurements that relate closely to body shape and size. In the present study, an individualized K_B value was derived as a function of weight and height rather than from the more time-consuming approach of obtaining the necessary anthropometric dimensional measurements. The approach adopted in the present study is conceptually similar to that used previously in using simply height and weight, but rather than using these combined as a single correction factor, BMI (Moissl *et al* 2006), each was used independently to predict K_B from the relationship between all three variables determined in a calibration population. This approach assumes that a relationship between K_B, weight and height exists, and varies in a systematic manner as body shape and size varies. This hypothesis was supported by the observations of the present study that change in K_B with height and weight could be well represented by a surface plane, which could be used as a calibration surface to estimate a K_B value for height-weight pairs. The relationship between K_B as the independent variable and height and weight as predictor variable could not be adequately represented by a multiple regression equation since this procedure assumes a perfectly flat surface.

Although prediction of K_B from height and weight was shown to have merit improving prediction of body composition in those with BMI <30 kgm^2, the method is clearly imperfect. Height and weight alone or combined as in BMI are not reflective of body shape or the relative masses/volumes of the body segments. Once adulthood is achieved, height changes very little decreasing slightly but progressively as one ages. Weight, one the other hand, varies markedly between individuals or within individuals over the life-span, or with disease and nutritional change. Accumulation or loss of body mass generally does not occur proportionally across the body segments. Accumulation of body fat may occur as increased appendicular subcutaneous adipose tissue or increased visceral and abdominal adipose mass; under these conditions two individuals with the same body mass would have different relative proportions of trunk to appendicular volume and K_B despite the same height-weight combination. This would not be detected by the present method, instead both would be predicted to have identical K_B values.

This confounding effect is most likely to be observed in those who are overweight or obese. Data from the present study provides support for this view. Body (excluding hands feet and head) and segment volumes were calculated from the anthropometric data for the K_B data sets. Segment volumes were computed assuming simple cylindrical geometry from the circumferential and length data for the body segments. There was no difference in trunk volume as a proportion of total volume for those with BMI < 25 kg/m^2 but from there on, relative trunk volume increased progressively as BMI increased (Figure 4). This suggests that as BMI increased K_B prediction would become progressively more inaccurate. This is reflected in individualized K_B values having no advantage over a fixed value of 4.3 when predicting FFM (Table 2). It is possible that a correction factor could be applied based on measurement of waist circumference as an index of increased trunk volume. Although this would require an extra measurement when using BIS, this is unlikely to be an onerous imposition since waist circumference is frequently measured in clinical practice in body composition studies (Ross *et al* 2020) although its accuracy has been questioned (Verweij *et al* 2013).

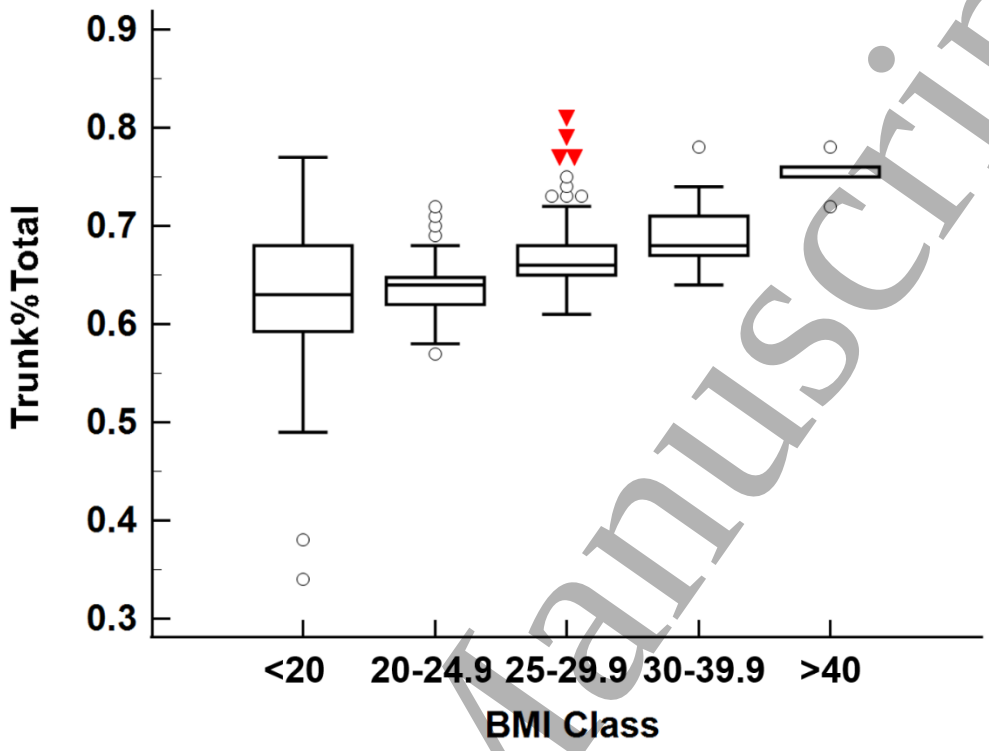

Figure 4. Change in relative volumes of the trunk and total body in individuals in the K_B data set (see Supplemental Data Table 1 for details).

A number of limitations to the study should be acknowledged. K_B values were calculated from readily available anthropometric data. These data were primarily sourced from anthropometric measurements used to derive standards for body sizing in the garment industry. These data are exclusively obtained from surveys undertaken in the general population of the USA. In addition, while the exact number of individuals providing data are unknown, the ASTM data are designed to be representative of the population. As such, they may not be a good reflection of other populations with notably different body habitus, for example Asian. Although the ASTM standards are updated regularly, they continue to include data from earlier decades. This problem of old data was also apparent in that other than the studies of Merlob there appear to be no single studies in neonates in which all the required measurements are available. Improvements in health and nutrition over this time could

potentially mean that the data used here do not reflect well contemporary populations. Precise methodological details for measurement methods are lacking but it is assumed that data were obtained in accordance with ASTM recommendations (ASTM International 2015a). Comparatively few data were available for infants and children, particularly with heights between 60 and 130 cm. The inadequacies of the current data could potentially be addressed by the use of data available from large surveys of populations using 3-D laser scanning (Koepke *et al* 2017, Santos *et al* 2016). Potentially, it may be possible to determine K_B from segmental volumes estimated from photographs obtained using a smartphone for an individual at the time of BIS measurement (Farina *et al* 2016, Majola 2020).

In conclusion, this study has demonstrated the potential advantage of using personalized K_B values in mixture theory when predicting body composition from BIS data. The method proposed, based on height and weight, anthropometric measurements already obtained as part of the BIS protocol requires further modification to be applicable across the broad range of body habitus seen in the human population. Improved performance may be possible through refinement of the K_B calibration using contemporary anthropometric data from laser scanning studies and by correction for central adiposity using waist circumference.

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